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BOEING INFRARED SENSOR (BIRS) CALIBRATION FACILITY

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ABSTRACT

The Boeing Infrared Sensor (BIRS) Calibration Facility represents a major capital investment by The Boeing Company in optical and infrared technology. The facility was designed and built for the calibration and testing of the new generation large aperture long wave infrared (LWIR) sensors, seekers and related technologies. Capability exists to perform both radiometric and goniometric calibrations of large infrared sensors under simulated environmental operating conditions. The system is presently configured for endoatmospheric calibrations with a uniform background field which can be set to simulate the expected mission background levels. During calibration, the sensor under test is also exposed to expected mission temperatures and pressures within the test chamber. Capability exists to convert the facility for exoatmospheric testing.

The first major test runs in the facility were completed during 1989 with very satisfactory results. This paper will describe the configuration of the system and hardware elements and address modifications made to date.

Pitt-Des Moines, Inc. (PDM) of Pittsburgh, PA was the contractor for the turnkey design and construction of the test chambers and thermal vacuum systems. Hughes Danbury Optical Systems (formerly Perkin Elemer Optical Systems) was the hardware supplier for the optical hardware. The Boeing Company performed all optical assembly, integration, testing and alignment on site.

INTRODUCTION & SYSTEM DESCRIPTION

The system consists of two major vacuum chambers, a small window subchamber, a mounting slab, an infrared source generator, beam expansion optics and a sensor support mount designed to support the sensor in a simulated operating environment. The system is shown schematically in Figure 1.

The BIRS vacuum chamber consists of two main chambers called the optics chamber (OC) and the sensor chamber (SC). The optics chamber is maintained at a pressure of 1.0×10^{-7} torr or lower and the equipment within the chamber operated at near liquid nitrogen temperature. This equipment includes the Beam Expansion (BX) optics and the Scan Mirror Assembly (SMA). The sensor chamber is held at a nominal pressure of 90 torr and a temperature of 220°K to 240°K.

INTRODUCTION & SYSTEM DESCRIPTION (Continued)

The Window Subchamber (WSC) is a third small chamber located between the optics and the sensor chamber and provides for isolation of the WSC optical elements during sensor installation by means of a 1.5m (60 inch) gate valve located on the sensor chamber side of the WSC. This allows the optical system to remain at high vacuum and low temperature conditions, maintaining its optical stability and eliminating the time required to warm up and cool down the optical system. This chamber is physically located within the optics chamber at the interface between the optics and sensor chamber.

The pressure boundary between the high vacuum optics chamber and the altitude sensor chamber during test is provided by an Output Window Assembly (OWA) located within the WSC. This large zinc sellenide infrared transmitting window passes the calibration beam from the optics chamber to the sensor chamber and also serves to reflect a uniform radiation background generated by the Background Signal Generator (BGSG) which is a high emissivity plate that radiates to the sensor pupil via reflection off a Background Signal Generator mirror and the OWA.

Figure 2 is a schematic elevation view of the optical system.

Infrared beam expansion is accomplished using the Beam Expander (BX) equipment which is located in the optics chamber. The BX is a three mirror afocal telescope which takes a collimated input beam from the Modified Portable Optics Sensor Tester (MPOST) (GFE) and expands it to a 0.8 meter (32 inch) collimated output beam. The BX mirrors and structure are normally cooled to near 80°K.

A Scan Mirror Assembly (SMA) is provided which reflects the input beam from MPOST into the BX optics. The SMA can be used to accurately position the stationary beam during the goniometric calibration mode and is used to scan the beam across the sensor during the radiometric calibration mode.

The input calibration beam is inserted into the optics chamber from MPOST via the Input Window Assembly (IWA). The IWA forms the contamination seal with the optics chamber incorporating an 11 inch diameter ZnSe window. This window in conjunction with the output window assembly also serves to remove polarization effects. It is capable of being cooled to 104°K with 80°K subcooled LN_2 when MPOST is attached to the chamber. Also included in this assembly is the input coldwell which is a series of optically dense baffles cooled to 80°K.

SYSTEM COMPONENTS

Optics Chamber

The optics chamber is a rectangular stiffened vacuum chamber having inside dimensions of 3.35m wide x 3.35m high x 5.5m long (11' wide x 11' high x 18' long). The material is 304 stainless steel with carbon steel stiffeners designed for the full vacuum load. The stainless steel interior surfaces are polished to a simulated No. 4 finish. The optics chamber rests upon the seismic slab which also supports the optical test equipment inside the chamber. Figure 3 is a schematic elevation of the optics chamber.

A full opening door is provided on one end of the chamber for optics system installation, alignment and maintenance. A rectangular configuration was chosen for this vessel and the sensor chamber. This decision was based on a trade study which indicated circular vessels would provide excess volume and would be difficult to connect to the seismic slab. Further, it was determined that a rectangular chamber better accommodates installation and removal of a thermal shroud around the beam expander and scan mirror structure. Optics Systems penetrations provided for the support legs of the beam expander and scan mirror are unique in that a flexible seal assembly was provided which decoupled the chamber shell from the leg so that no detrimental vibratory inputs were transmitted into the optics system. The optics chamber is fully lined with an optically dense LN_2 cooled shroud. External valved cryopumps provide high vacuum pumping.

Sensor Chamber

The sensor chamber is also a rectangular stiffened vacuum chamber having inside dimensions of 4.9m wide x 4.6m high x 7m long (16' wide x 15' high x 23' long). Chamber materials are Type 304 stainless steel. Carbon steel stiffeners are provided to resist full vacuum load. The sensor chamber is hard mounted to the seismic slab which also provides independent support for the sensor assembly by a series of legs penetrating the shell. These legs are decoupled from the chamber shell identically to the optical elements described previously.

The sensor chamber is provided with two full cross sectional opening doors, providing full access to the interior for loading and unloading the sensor. In addition, a personnel door is provided in one of the full opening doors to allow entry to the sensor chamber without removal of the full door. Figure 4 is a schematic elevation of the sensor chamber looking toward the sensor chamber.

In addition to the penetrations for the sensor mount system legs, the chamber is provided with a 1.5 meter (60 inch) diameter penetration for a remotely operated gate valve which isolates the window subchamber from the sensor chamber. The design and operation of the gate valve will be described later.

Sensor Chamber (Continued)

The sensor chamber is fully lined with a unique, passive thermal shield (insulation system) which isolates the chamber shell from the nominal 13,715m (45,000 feet) altitude environment, i.e. 90 torr and -45°C. This insulation system consists of a rigid polystyrene foam with a stainless steel skin which is evacuated to a low micron level. This provides an effective insulation for the external chamber shell from the high altitude environment of the sensor chamber.

Vacuum Systems

Optics Chamber

The vacuum systems for the optics chamber consists of:

1. A mechanical pump/blower combination with LN_2 cold trap capable of rough pumping to less than 50 microns.
2. Three 500mm (20 inch) diameter externally mounted cryopumps provide high vacuum pumping to 1×10^{-8} torr. Each is equipped with a large diameter isolation valve.
3. A 150mm (6 inch) turbomolecular pump is provided with a manifold allowing it to pump either the optics or sensor chamber. This pump is primarily used during the leak checking phases.

Sensor Chamber

The vacuum system for the sensor chamber consists of a 3-stage blower system capable of roughing the sensor chamber from 760 to 90 torr with a simultaneous 0.23 kg/sec (0.5 lb/sec) GN_2 inbleed. The roughing system is also capable of pumping 0.16 kg/sec (0.35 lb/sec) GN_2 inbleed while maintaining the pressure between 90 to 60 torr.

LN_2 Thermal System

The LN_2 thermal system is comprised of a recirculating LN_2 system operating in a subcooled mode with the heat gain being rejected into a bath of boiling LN_2 at atmospheric pressure. This system is shown schematically in Figure 5.

The heat loads on the system are as follows:

- Optics Chamber Shroud Zones
- Beam Expander & Scan Mirror Zones
- Scan Mirror & Input Window Assemblies
- MPOST Zones
- Sensor Chamber Zones (future)

LN_2 Thermal System (Continued)

These systems are supplied liquid nitrogen at approximately 80°K and return liquid to the cooling coil in the dewar at approximately 95°K or less, depending on the heat load in each respective system.

In addition to recirculating loads described above, the LN_2 subcooler furnishes LN_2 for two GN_2 thermal units. These units are consumers of LN_2 on a continuous basis requiring make up of LN_2 into the recirculating LN_2 stream. LN_2 make up is accomplished by reducing the pressure on the suction side of the LN_2 pumps and injecting make up LN_2 in the low pressure zone from an external storage tank operating at about 48.3 kPa (7 psig). Pressure reduction is accomplished by a throttle valve located before the connection to the external LN_2 tank.

The subcooler has the capability of absorbing 85,900 kcal/hr (100 kw) of heat from the system while maintaining all operating heat loads (zones) at a nominal temperature of 80°K. Uniformity of the supply temperature is critical to the stability of the optical elements. During baseline operation, temperature stability is maintained within ± 1K.

The optics chamber shroud construction consists of extruded aluminum panels having integral tube passages. The emissivity of the shroud on the inside surface is 0.9 with the side facing the chamber 0.1. The design of the shroud is unique in that all penetrations and closures prevent any surface outside of the shroud with a temperature of 95°K or greater from being observed with less than 2 reflections off optically dense baffling with a surface emittance of greater than 0.9. The shrouds are also removable from the chamber for cleaning. Conflat flange LN_2 connections are provided for each shroud section. These connections are interior to vacuum chamber and underwent extensive leak checking during the acceptance test program to ensure leak tight performance.

GN_2 Thermal Systems

Two GN_2 thermal units are provided. The sensor chamber thermal unit has the primary function of providing a cold inbleed gas source to maintain the sensor chamber at ambient temperatures consistent with altitude operation at 60 torr to 90 torr while being actively pumped by the sensor chamber roughing system. This inbleed in effect subjects the sensor unit under test to environmental conditions as though it were "flying" at altitude. GN_2 is supplied to the sensor chamber thermal unit by an LN_2 vaporizer operating from a conventional LN_2 storage tank. A stream of LN_2 from the subcooler is mixed to the GN_2 stream in an LN_2/GN_2 mixer to provide a varying output stream temperature between 140°K - 300°K with a maximum throughput of 0.32 kg/sec (0.7 lb/sec). The unit is also provided with a warmup heater for use in warming optics' chamber shrouds and optics zones. This unit is shown schematically in Figure 6.

GN_2 Thermal Systems (Continued)

The other GN_2 thermal unit has the function of providing temperature controlled GN_2 to a group of zones in the window subchamber and sensor chamber. It circulates GN_2 on a closed loop basis. This is accomplished by using a conventional reciprocating compressor in series with an aftercooler, heat exchangers, heaters, LN_2/GN_2 mixer, preheaters and trim heaters. This system is shown schematically in Figure 7. GN_2 is supplied to this system from the same high pressure storage vaporizer system that supplies the sensor chamber thermal unit. A pressure regulator in this supply line reduces the pressure to 172.4 kPa (25 psig) and subsequently through downstream heat exchangers, etc. to ultimately serve as a thermal conditioning fluid for end users in the window subchamber and gate valve. Two output streams are provided which can be set at different temperatures. From these use points the gas is recirculated back to compressor suction. This system has the capacity of circulating 365 kg/hr (800 lb/hr) in a temperature range of 140°K to 300°K at a maximum pressure of 414 kPa (60 psig). A key requirement of this unit is providing the GN_2 which cools the titanium adapter for the OWA. Accurate temperature stability is required so as not to induce thermal strains in the OWA bezel structure.

Control System

The BIRS facility is controlled from a central control console that is functionally divided into three sections:

- Thermal-Vacuum Control
- Optical Control
- Data Acquisition System

The thermal-vacuum control console section receives data from facility instrumentation which displays on an integrated graphics panel which has associated symbolic and written legends defining system control functions. All remote facility operations are manually controlled from this panel with the status of all major functions displayed. Alarms and interlocking of all functions are accomplished at this panel. Control logic and interlocks were provided by means of a PLC (Programmable Logic Controller). An effort was made to limit the amount of interlocks to as few as possible to allow for maximum operator flexibility and test configurations. Redundant PLC's were not provided; however, all equipment and valves have been designed to go to a failsafe mode in the event of a system failure. The PLC provides automatic operation of the system in the event of designated emergencies, such as loss of prime power or overpressure of the OWA. The optical control system allows for monitoring and setting of temperatures of all optical elements and provides control capability of the Sensor Mount Subsystem (SMS) and Scan Mirror Assembly (SMA). The data acquisition system gathers and records all facility data and provides real time plots of data showing trends, etc.

Key Optical Elements

Beam Expander

The Beam Expander (BX) enlarges the incoming source beam to approximately 3 times its initial diameter. It is an afocal system with a Cassegrain telescope consisting of parabolic input or tertiary mirror coupled to a hyperbolic secondary and parabolic primary mirror. The BX is off-axis in both field and aperture and thereby provides an unobscured collimated output beam of approximately 0.8 meters (32 inch) in the present configuration. The primary mirror is a nominal 1 meter (41 inch) diameter solid piece of zerodur weighing over 409 kg (900 lbs). The tertiary mirror also of solid zerodur is nominally 0.76 meters (30 inches) diameter and weighs 136 kg (300 lbs). The secondary mirror is much smaller and is fabricated of fused silica. All mirrors have gold coating and protective overcoats. The LN_2 cooled BX optical bench is fabricated from Invar 36 for minimum dimensional variations from ambient to cryogenic conditions. Figure 8 shows a representation of the beam expander and mirrors.

Scan Mirror Assembly (SMA)

The SMA consists of a servo driven cryogenically cooled fused silica mirror assembly which allows the accurate positioning of the output beam when used in the stare mode. In the scanning mode, the SMA allows the output beam to be scanned across the test sensor at various rates. Azimuth and elevation servo electronics are controlled by computer.

Output Window Assembly (OWA)

The Output Window is one of the most important single components in the facility. The ZnSe blank was generated by a continuous and uninterrupted chemical vapor deposition oven run of over 900 hours. The finished window is 0.79m (31-inches) in diameter and 33mm (1.3 inches) thick and represents the largest ZnSe window of its type in the world. As with the Input Window, the Output Window is mounted in a titanium bezel for CTE matching. It is held in place by a thin bead of Crest 7450 adhesive around the perimeter which also forms the vacuum seal. Special heaters precisely control the edge temperature of the window. Because of the small thickness to diameter ratio, the window is not capable of supporting a full atmospheric pressure load. For safety, it is limited to differential pressure loads of the order of 120 torr. The purpose of the Window sub-chamber with the 1.5m (60 inch) Gate Valve to the Sensor chamber is to maintain the controlled Output Window pressure load while allowing free access to the Sensor Chamber.

Special Features

The stringent requirements of providing an optimum environment for the optics system and sensor required that the vacuum chambers and supporting subsystems accommodate many unique operating criteria. The following items are herein described to identify some of these components and system requirements.

Seismic Slab

A seismic slab was provided to minimize the optical system components response to vibrations from the environment and the experiment itself. A schematic of this system is shown in Figure 9. A ground vibration survey was conducted at the facility site as well as identification of other disturbances such as vehicular traffic, cranes, local handling equipment, pumps, etc.

Criteria for structural and dynamic requirements for the seismic slab are as follows:

a) Optical beam drift due to seismic slab deformations to be less than 0.5 microradian over a 1-30 minute time period.
b) Long term drift (deformation) were to be minimized by design, material choice and fabrication control. Included in this requirement is the prevention of cracking of the seismic slab.
c) Provision for a procedure to determine when a recalibration of the slab is required due to change in shape of the seismic slab as a result of curving due to temperature gradients.

In order to satisfy these requirements, an 1800 metric ton concrete slab disconnected from the building floor slab was selected to be supported on piling driven to a load bearing stratum. A dynamic vibration analysis was carried out to determine that the short term beam jitter could be accommodated.

Horizontal and vertical vibration data were collected for the BIRS site. This data was put into the form of a site specific response spectra which provided a range of frequency dependent accelerations resulting from the ground vibrations. A computer model of the chamber, seismic slab, and optical mounts connected to the seismic slab was prepared. The response of this model to the accelerations determined by the ground vibration study was calculated and compared to the allowable response "budget" for the optical system.

To limit vibrations into the chamber from rotating mechanical equipment and piping, all vacuum pumping skids, LN_2 pumping systems and GN_2 thermal units were mounted on vibration isolation mounts. Flexible metal hoses were used throughout the piping system to reduce vibrations into the chamber.

In order to meet the long term drift requirement, the services of a concrete design specialist was obtained to provide a design of a concrete mix and reinforcing which would minimize long term creep and cracking. Crack control reinforcing steel and low heat of hydration concrete was used in the seismic slab to ensure slab performance. The pouring sequence of the slab was carefully controlled and monitored as well. The slab is provided with an inspection gallery around its perimeter for visual inspection of the slab for cracking and signs of distress across its full thickness. For the recalibration requirement, a series of thermocouples were embedded in the concrete to measure temperatures. This data was used to determine any differentials that might exist (vertically and horizontally) that would cause geometric movement of the top surface of the slab.

Sensor Chamber Gate Valve

A large 1.5 meter (60 inch) diameter remotely controlled gate valve was provided to isolate the sensor chamber environment from the output window. Also, it serves to isolate the window subchamber during the period of window temperature conditioning.

Some of the specific design requirements for the valve were as follows:

- Valve to be remotely operable to cover and seal the window subchamber at one atmosphere differential pressure.
- Valve closure repeatability to be ± 1.7 mm (± 0.065 inch) (a calibration mirror is located on the inside of the gate valve).
- The seal of the gate valve (O-ring) was required to be warm to permit operation and sealing at all chamber conditions.

To achieve the remotely operable requirement, the valve assembly was suspended from an upper rail system which laterally translated the valve cover to allow a full diameter opening. Translation was achieved by using a roller chain drive system which was powered by a motorized worm gear reducer operating through a fluidic coupling. Use of the roller chain system also allowed for accurate position indication and adaptation of suitable interlocks with other systems. Once the valve gate seal plate is positioned over the mating flange, initial contact pressure for the seal is accomplished with four pneumatic cylinders which reach between the carriage frame and the valve plate. In order to maintain the seal at a warm condition, both the flanges and the O-ring seal were provided with a series of strip heaters mounted on each flange, clamped into contact and energized as required to maintain the metal temperatures above freezing for all operating conditions. Heaters are shielded from the view of the test sensor. Connected to the gate valve are shroud components which move into position when the gate valve is moved away from the window subchamber, thereby allowing the optical beam to pass onto the sensor. The shroud components operate nominally between 220°K and 250°K using GN_2 as a cooling medium. Supply to these shroud components required a festooning system for GN_2 supply hoses and instrumentation wiring.

Sensor Chamber Insulation

The specification required that the sensor chamber be designed with a passive thermal shroud which would isolate the chamber shell from the 90 torr, low temperature environment. The objective of this isolation was to prevent condensation on the external surfaces of the chamber. The internal insulation was to have a metallic surface to facilitate cleaning. Details of the system are shown on Figure 10.

Sensor Chamber Insulation (Continued)

Consideration of an externally applied insulation was not practical considering vessel sealing, stiffeners and appurtenances such as penetrations let alone the room cleanliness considerations (Class 10,000). The design that resulted to satisfy the above criteria was to apply a load bearing insulation material to the interior face of the chamber wall, cover the insulation with a metallic skin, and evacuate the space between the skin and the chamber wall to minimize the internal pressure load on the thin skin. The insulation material chosen was a load bearing styrofoam applied in two layers with staggered seams. The rigid insulation was held in place by use of thermally non-conducting studs as shown in the figure. Once the insulation had been applied, embedments were attached to the inside face of the insulation that served as retainer points which maintained the stainless steel skin in intimate contact with the insulation. These retainers allowed the skin to thermally move yet maintain proper support. All joints in the metallic skin were seal welded and leak checked to verify leak tightness.

Valve Box

As was discussed previously for the LN_2 and GN_2 thermal control systems, the facility utilized a considerable number of flow control (zone) valves. The normal method of insulation for such valves is to either mechanically insulate the valve with conventional insulation, or to provide a vacuum around the portion of the valve subject to low temperature with appropriate bonnet lengths to provide a thermal distance piece. This project required approximately 36 small diameter zone control valves. The insulation and arrangement concept employed was to utilize an arrangement called a "valve-box". It consists of collecting the valves into as small a region as possible and providing a common vacuum enclosure which provides the insulation required. Schematically, this arrangement is shown in Figure 11. Each valve is arranged such that the bonnet and operator extend through the face of the valve box for normal actuator connections. To enable the maximum number of valves to be placed in the valve box, the electronic to pneumatic converters used for control valve positioning were mounted on a separate rack adjacent to the valve box. This saved considerable space on the valve box since only pneumatic tubing was required to be run to the valves. Piping connections to the valves are made inside the box and pass through an isolation plate prior to entering the independent vacuum space of the respective chamber. Pumping of the valve box is accomplished with a small cryopump or turbo pump. Vacuum is maintained in the valve box in the same manner as would be accomplished in a vacuum jacketed dewar of large size. All internal lines are insulated with MLI to minimize radiation heat loads.

Modifications

For a facility with the complexity and size of BIRS, it is inevitable that various problems will surface that were not anticipated. The challenge of the facility team is to find solutions to the problems without affecting the performance and functionality of other parts of the system. Several problems of this type were found in BIRS as a result of our first sensor tests. Those noteworthy of mention iclude the compliances of the Sensor Mount Subsystem (SMS) and the overheating of the SMA azimuth motor.

Sensor Mount Subsystem (SMS)

The SMS is a three point kinematic mount system with 6 degree of freedom adjustability for fine positioning of a test sensor in front of the BIRS beam. This system can be operated remotely with the chamber under test conditions of temperature and pressure. During an initial sensor warm functional checkout, it was discovered that a significant motion of the sensor support platform was occurring in the longitudinal (parallel to SC axis) axis. Compliances in the system elements and the nature of the design to provide longitudinal positioning were determined to be the causes of this motion which was unacceptable both from a chamber integrity standpoint and for sensor stability. An ingenious system of high pressure locking struts was developed and tested in the laboratory. See Figure 12. The telescoping struts with high tolerance end bearings would allow positioning of the test article within the SMS range of motion. Once positioning was completed, the locking collars were pressurized with GN_2 to 20,685 kPa (3,000 psig) effectively locking the strut into a rigid unit. One end of the strut was connected directly to the sensor leg mounting block and the other to the main chamber leg support structure. This in essence provided a direct link from the sensor platform to the seismic slab embedded pedestal bypassing the total SMS mechanism and compliances. Resulting stiffness increases were on the order of a factor of 500 to 1. Observed motions dropped from the 1.27 cm (0.5 inch) range to the 0.05 mm (0.002 inch) range.

SMA Azimuth Motor Overheating

During initial testing, it was determined that the existing azimuth motor would overheat during periods of sustained scanning or staring at points near the edge of the angular range. A careful study and subsequent testing of a surrogate winding indicated that the problem was insufficient heat transfer from the windings to the cryogenically cooled core/case assembly. To rework this motor would require the removal of the SMA from the chamber and subsequent total disassembly. All alignment work of the optics would have to be redone. Since these were not desirable alternatives, both cost and schedule wise, a design was developed to retrofit the SMA in place using an externally mounted cryogenically cooled linear motor assembly. This linear motor actuates the mirror along the edge of the horizontal axis creating a moment arm rather than acting directly on the azimuth axis of rotation.

The motor is designed to meet all the existing SMA performance parameters and will use the existing servo control system. Presently, this modification is in the process of final installation.

SUMMARY & FUTURE OBJECTIVES

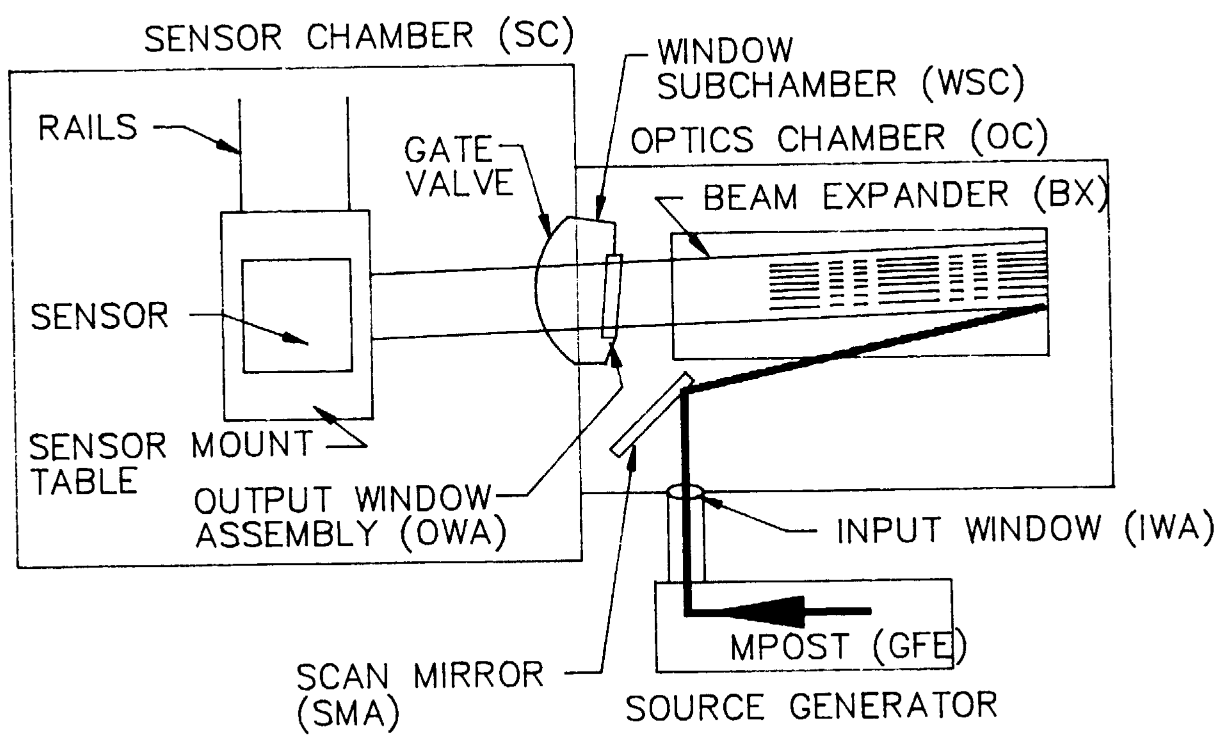
This paper has presented a summary of the key features and configuration of the BIRS system. Insight has been provided on several interesting problems that were encountered and their solutions. As is the case in most facilities of this type, new challenges arise as each test progresses.

SUMMARY & FUTURE OBJECTIVES (Continued)

While the present configuration of the facility is geared toward a specific testing requirement, the BIRS facility was designed to accommodate growth and adaptation to other capabilities. While it is not possible to build a facility capable of meeting all test requirements for projects in the future, it was possible to provide a sound baseline facility which can be used as a starting point for future test programs. Initial planning has been performed to support growth in the following areas:

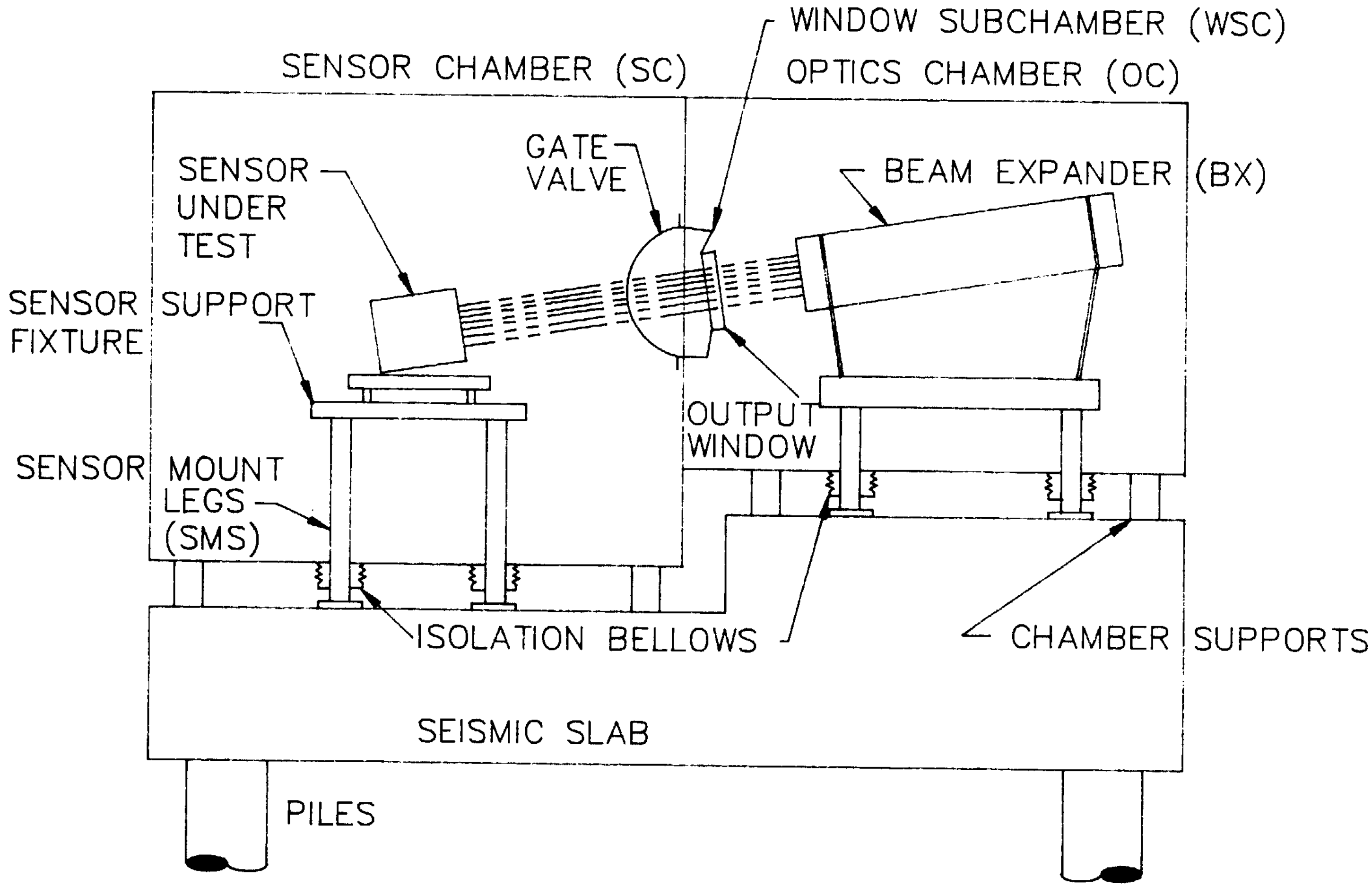
- Add capability to calibrate exoatmospheric sensors
- Add capability to test and calibrate space optical systems
- Develop hardware-in-the-loop capability

The facility represents a significant capability for infrared testing and calibration and will be available to all members of the U.S. infrared community. It is anticipated that this will include both support to government programs and other aerospace companies.



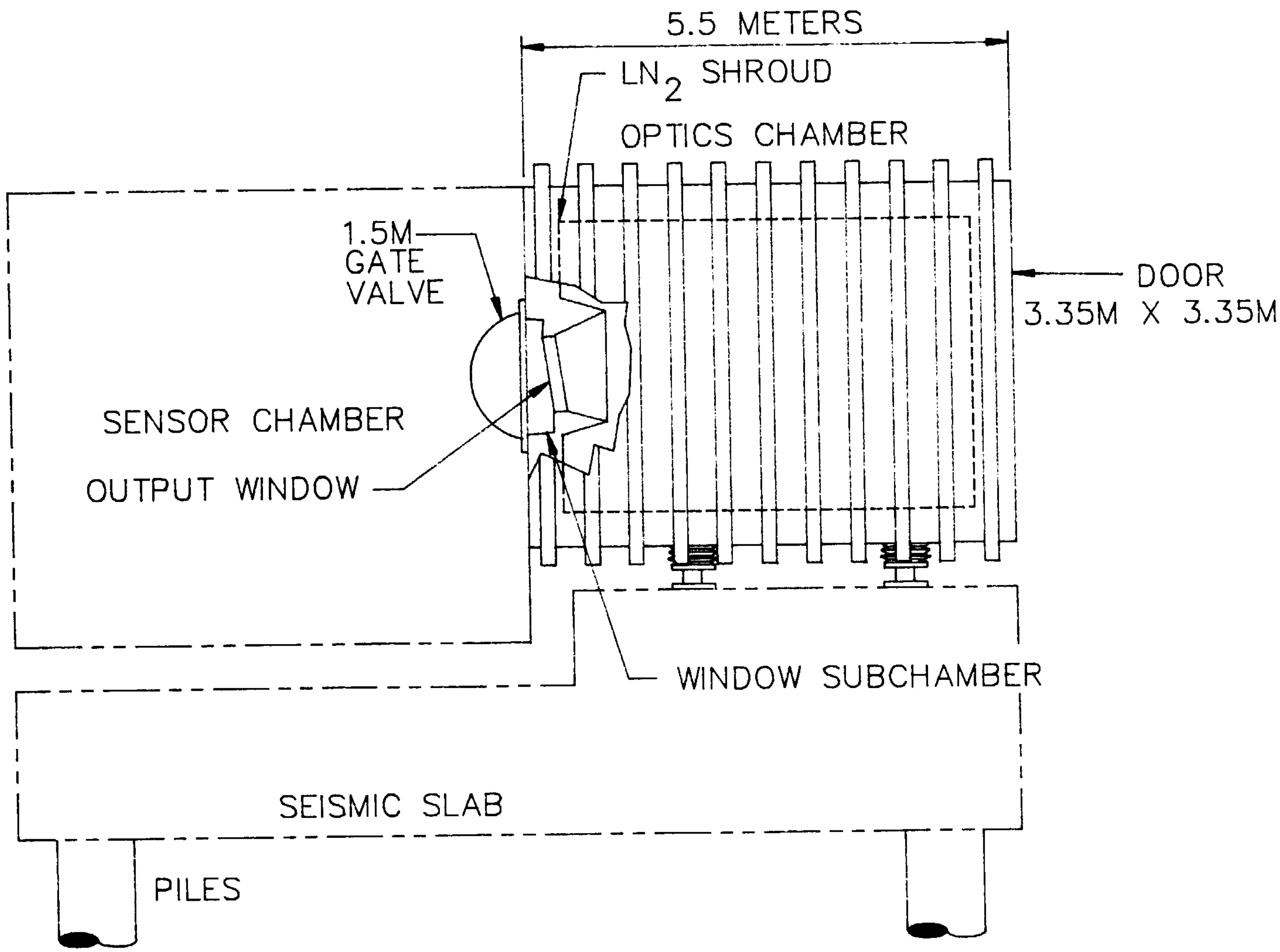
SCHEMATIC PLAN VIEW OF BIRS FACILITY

FIGURE 1



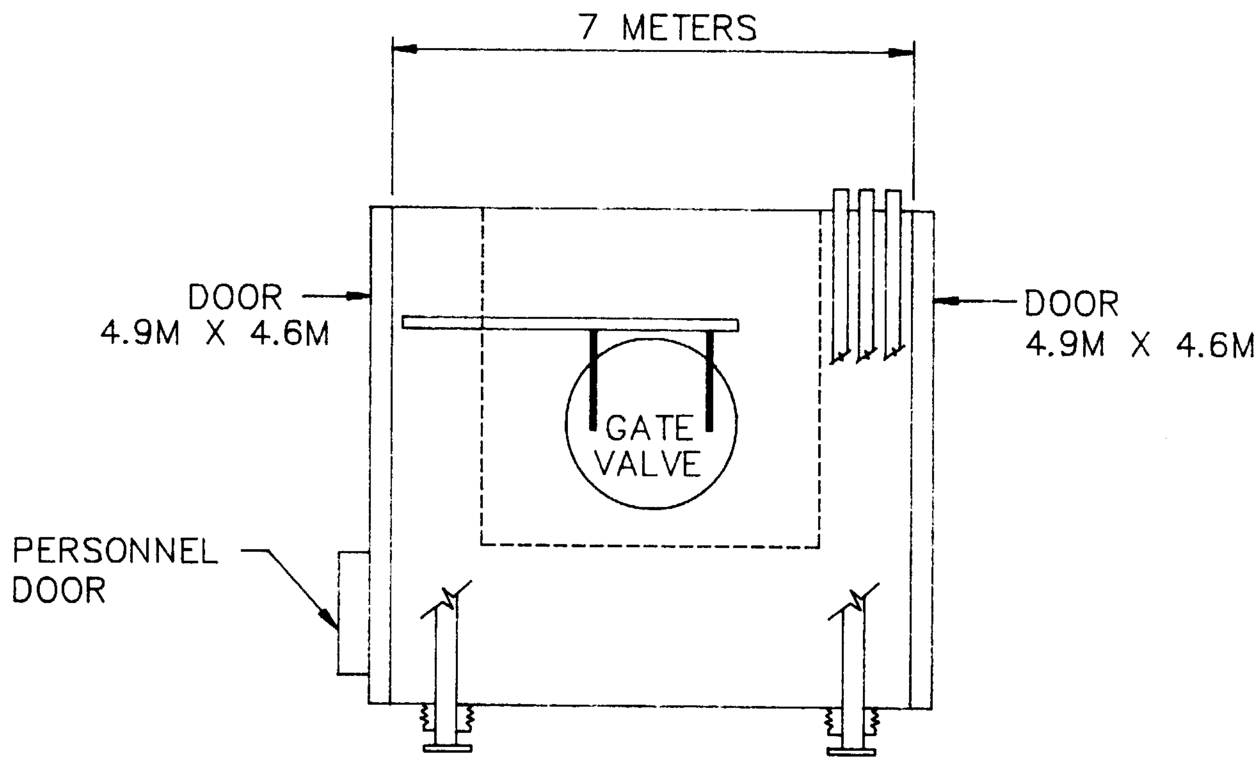
SCHEMATIC ELEVATION VIEW OF BIRS FACILITY

FIGURE 2



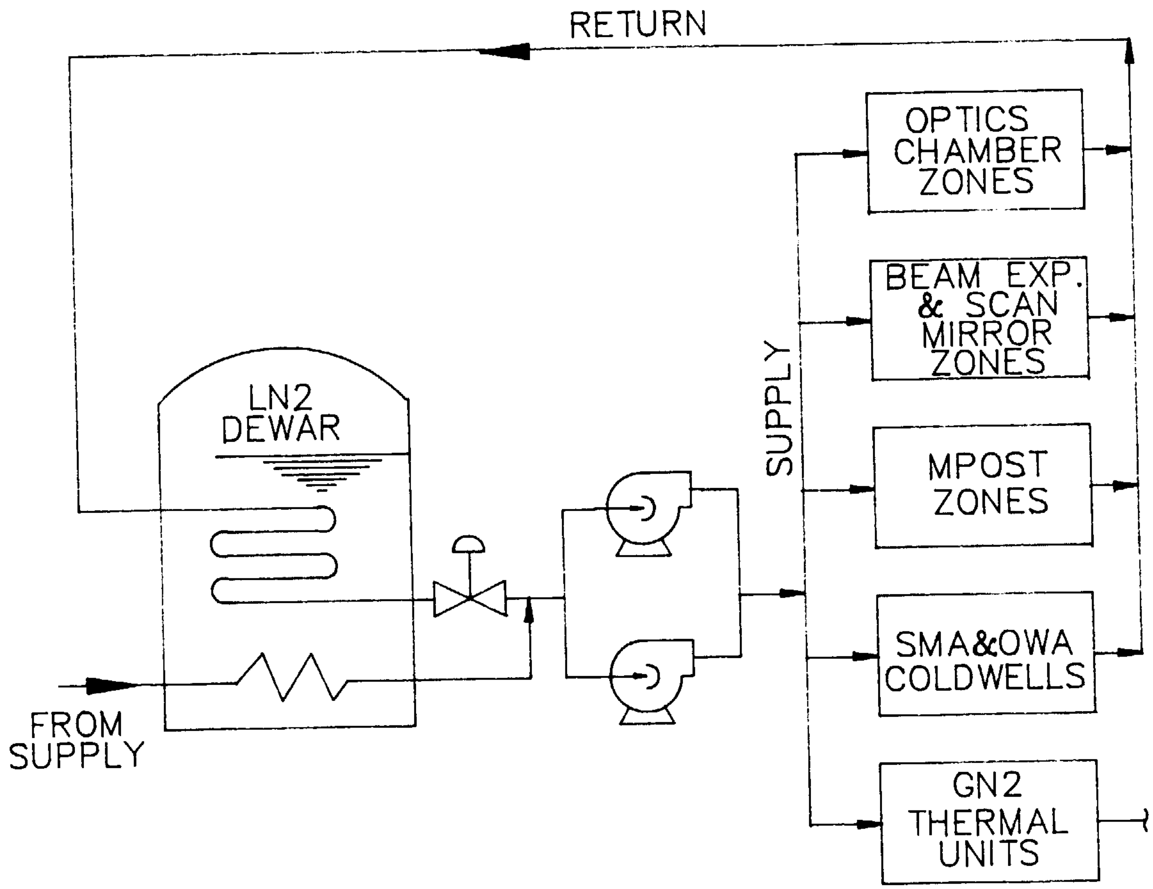
ELEVATION VIEW OF OPTICS CHAMBER

FIGURE 3



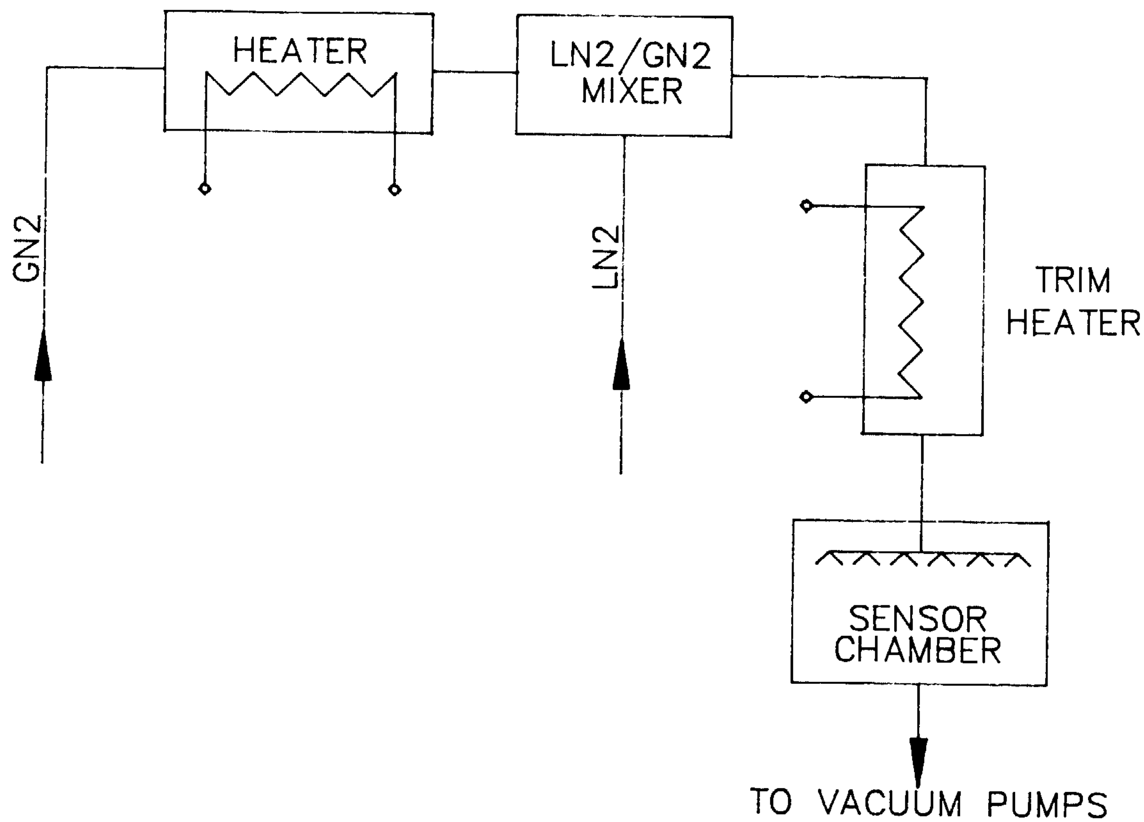
ELEVATION VIEW OF SENSOR CHAMBER
LOOKING TOWARDS OPTICS CHAMBER

FIGURE 4



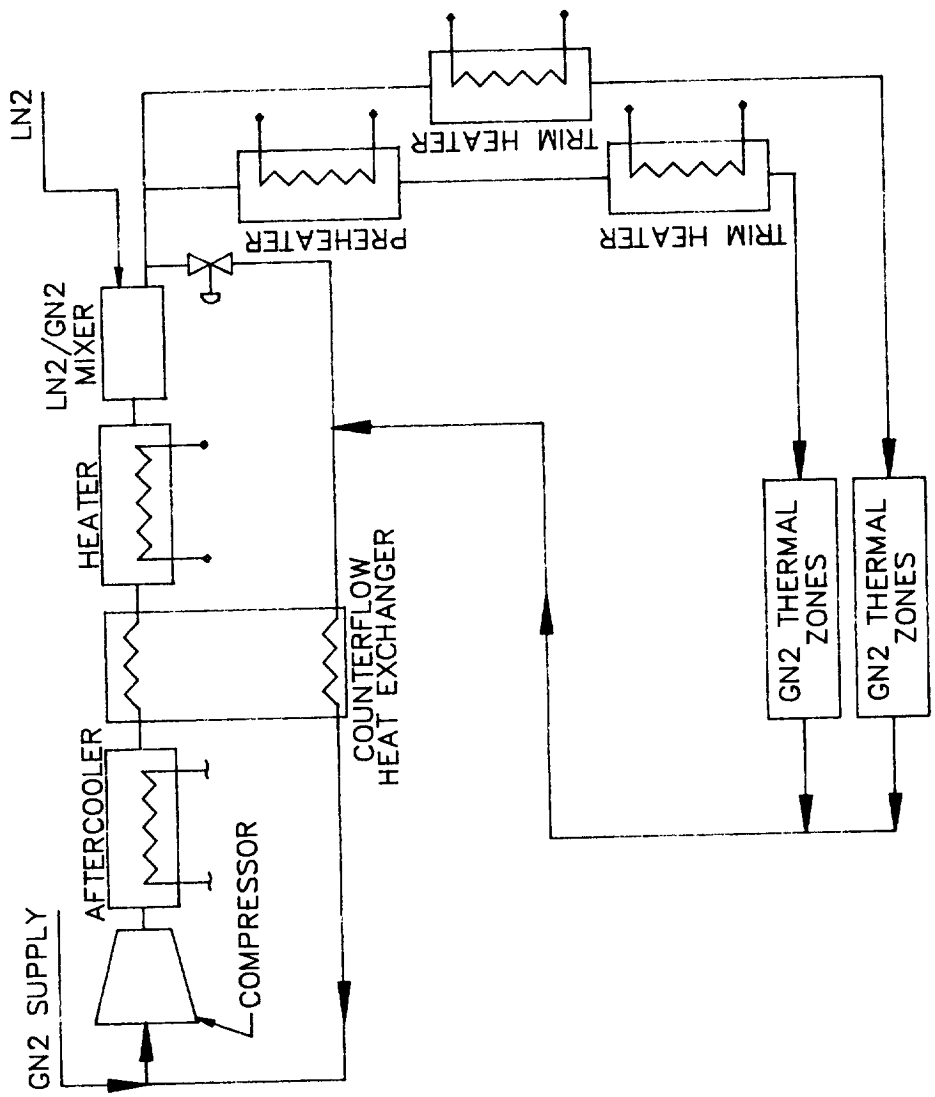
LIQUID NITROGEN THERMAL SYSTEM

FIGURE 5



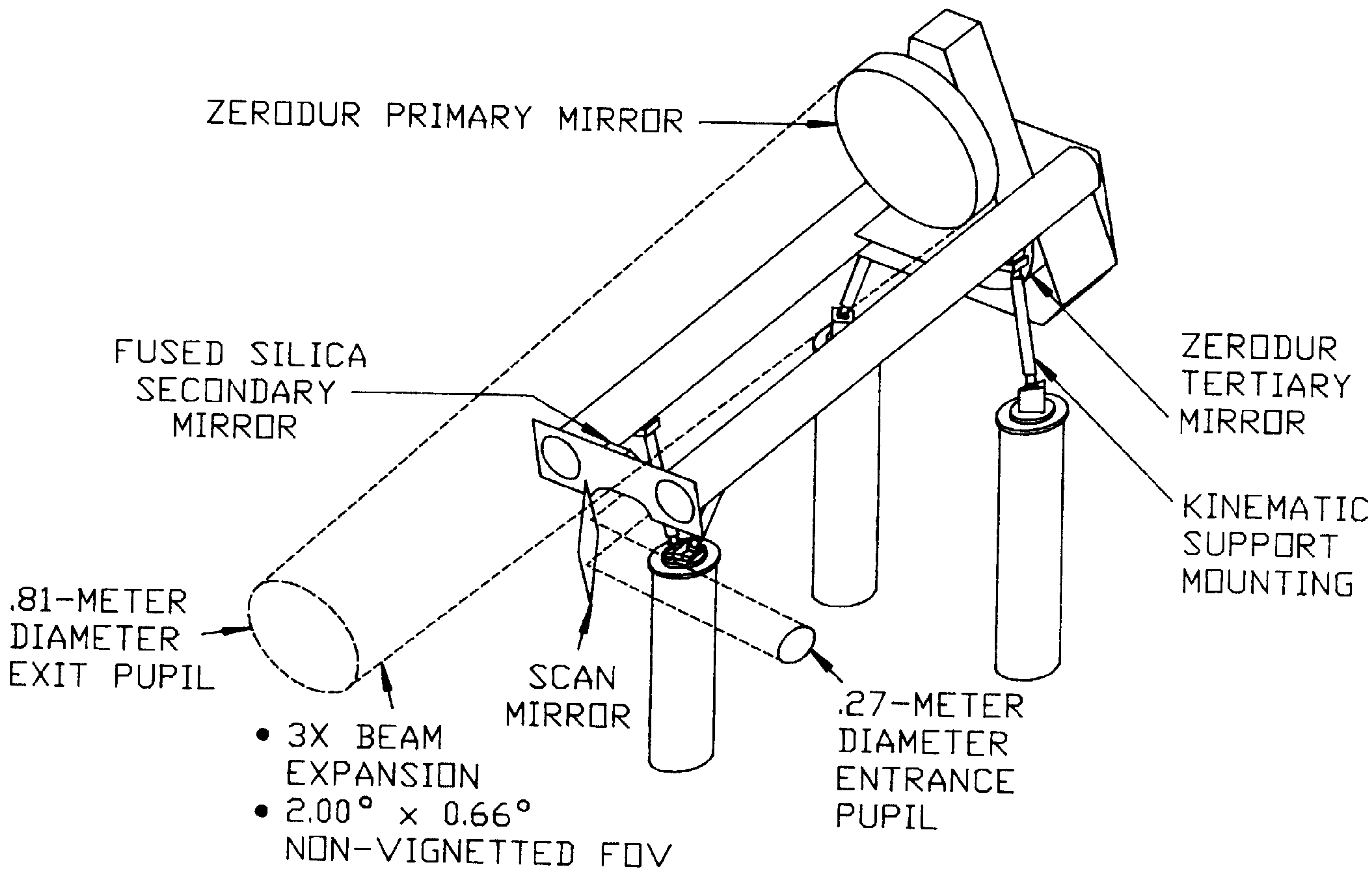
SENSOR CHAMBER GN2 THERMAL UNIT

FIGURE 6



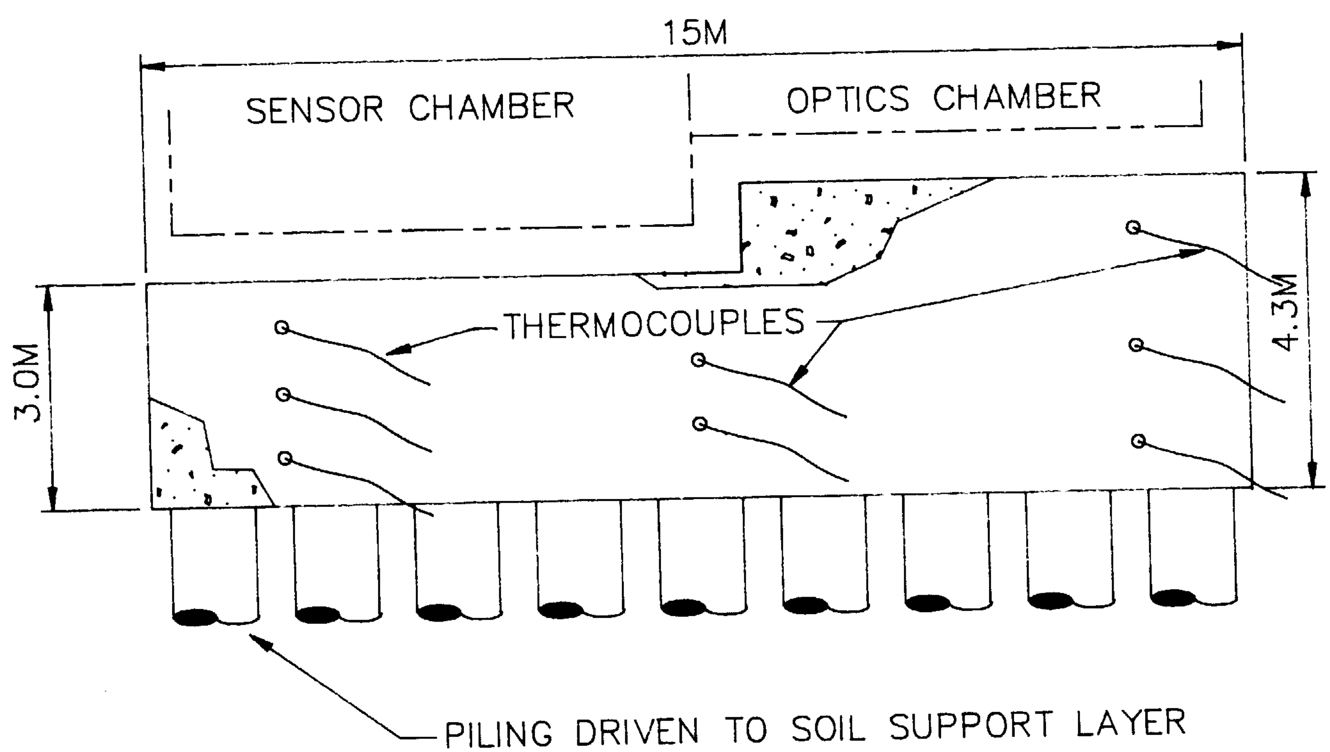
RECIRCULATING GN2 THERMAL UNIT

FIGURE 7



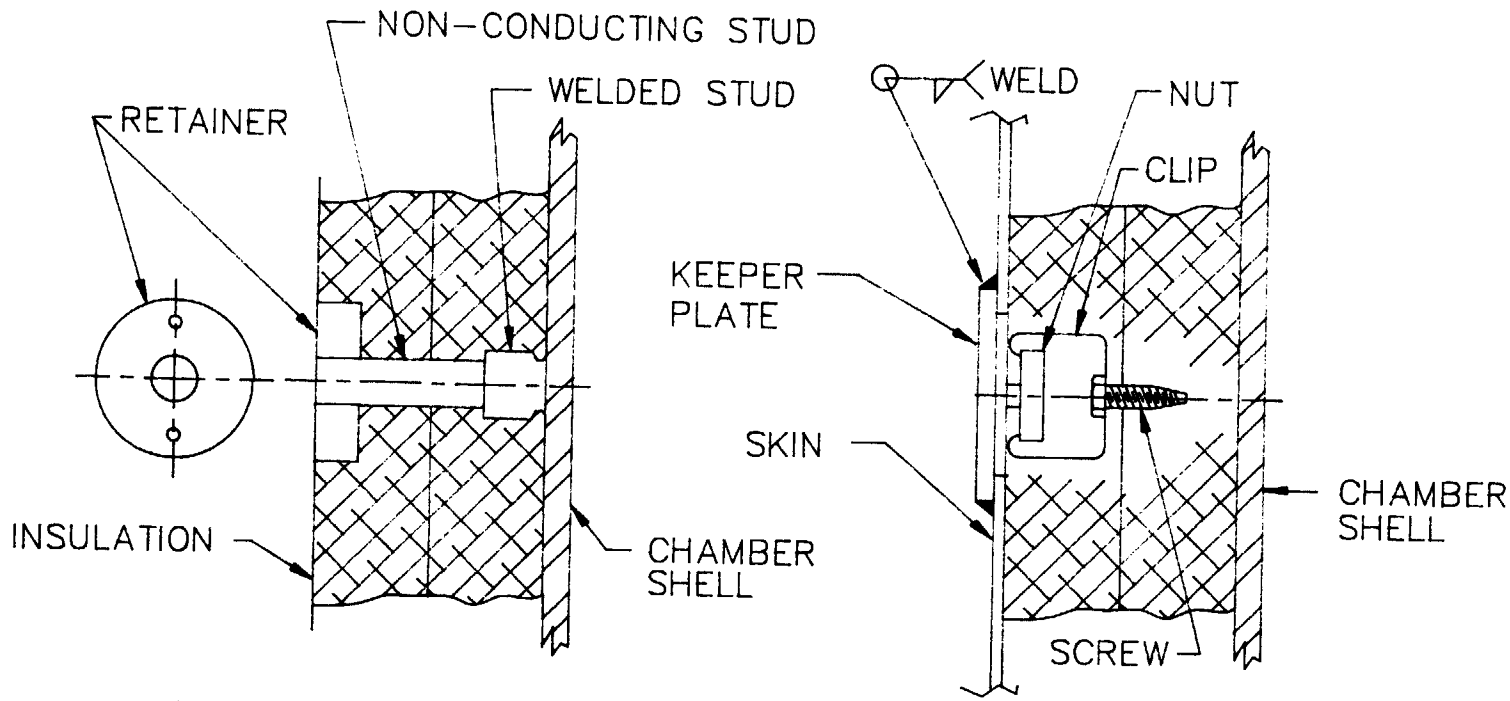
BIRS BEAM EXPANDER

FIGURE 8



1815 TONNE SEISMIC SLAB

FIGURE. 9

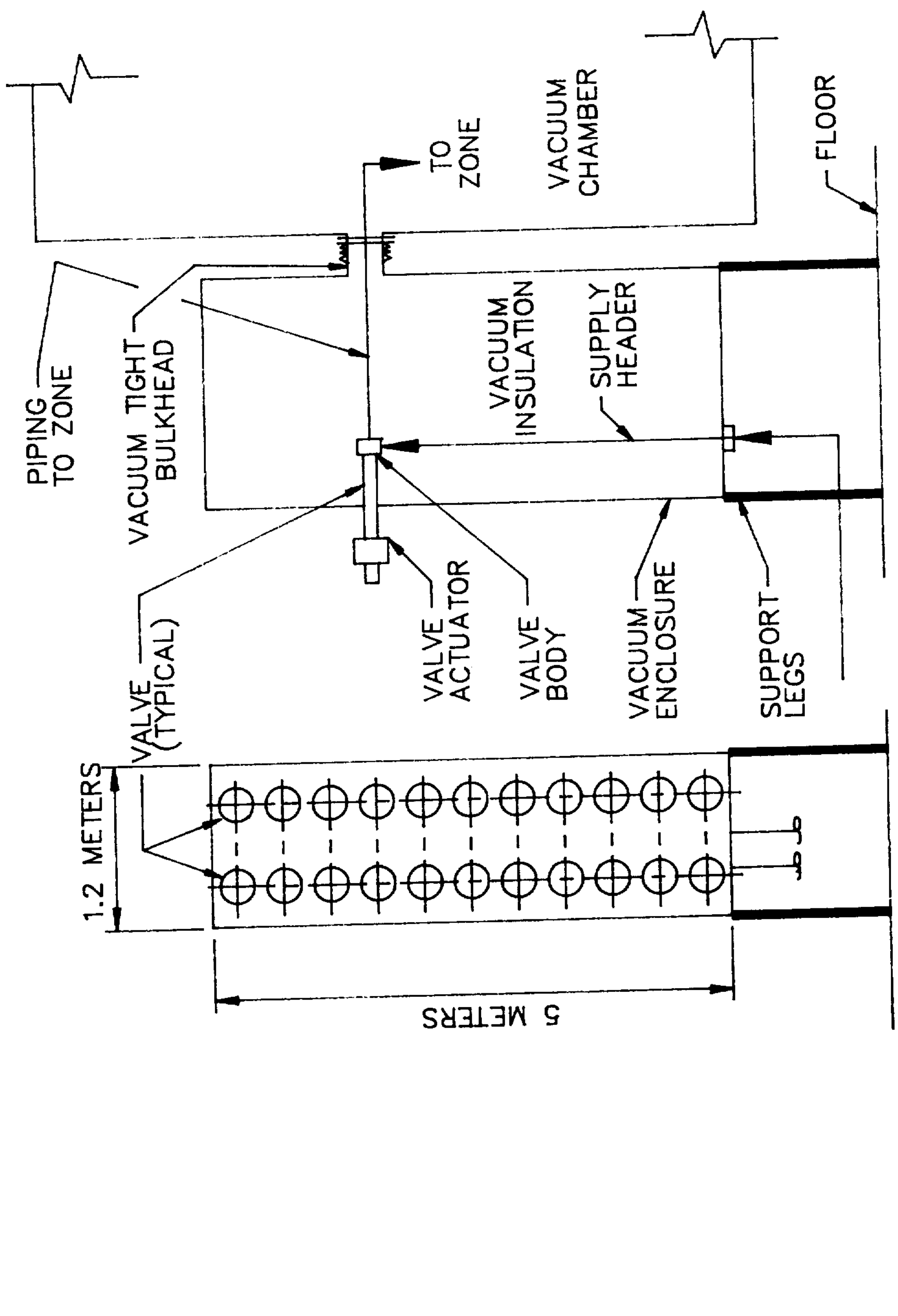


INSULATION ATTACHMENT TO SHELL

S.S. SKIN ATTACHMENT TO INSULATION

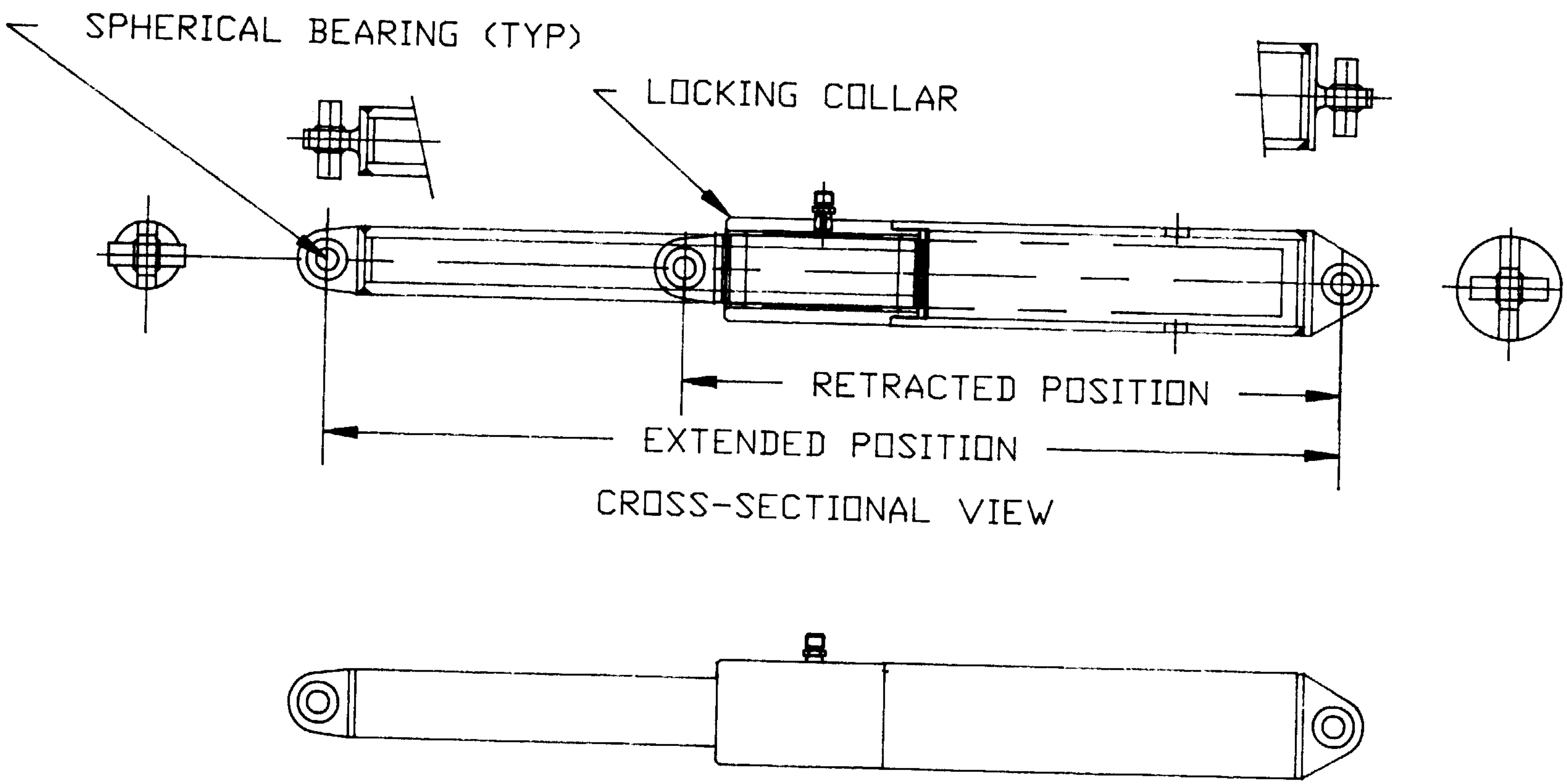
SENSOR CHAMBER INSULATION

FIGURE 10



VALVE BOX SCHEMATIC

FIGURE 11



SENSOR MOUNT SUBSYSTEM LOCKING STRUT
FIGURE 12